National Research Nuclear University “MEPhI”
http://www.mephi.ru

SPELS
Specialized Electronic Systems
http://www.spels.ru

Recent Advances in Single-Event Effects Qualification Tests of Modern VLSI ICs Based on Local Laser Irradiation

O. Mavritskii, A. Egorov, A. Chumakov, A. Pechenkin

E-mail: obmavr@spels.ru

Contents

- Introduction
- Focused Laser Irradiation (FLI) technique, possibilities and limitations
- What is Local Laser Irradiation (LLI)?
- LLI technique algorithm, how it works?
- Examples of modern VLSI IC qualification tests, based on *front-side* and *backside* LLI technique
- LLI technique problems, new trends
- Conclusion

Pulsed laser techniques

Single-Photon Absorption (SPA)

Two-Photon Absorption (TPA)

Both SPA and TPA of ultra-short laser pulses are widely used for scientific investigations.

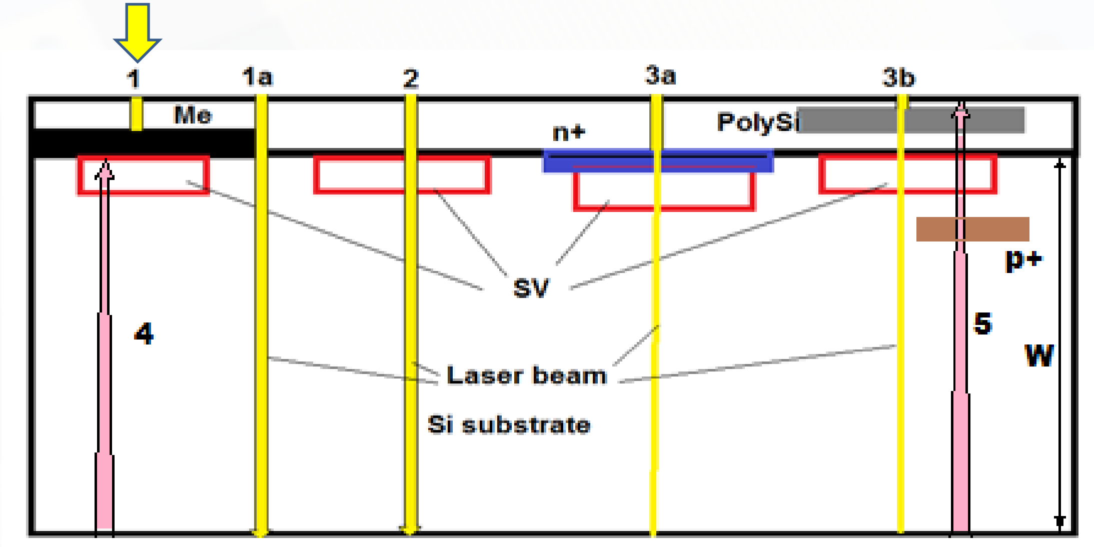
Today only SPA laser techniques *are <u>officially allowed in Russia</u> to be used for <u>radiation hardness testing</u> of semiconductor electronics:*

1. Focused Laser Irradiation + ion (or proton) calibration

2. Local Laser Irradiation

→ *only SPA for testing is discussed below …*

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization

Backside

4 – Absorption in substrate and reflection from metallization

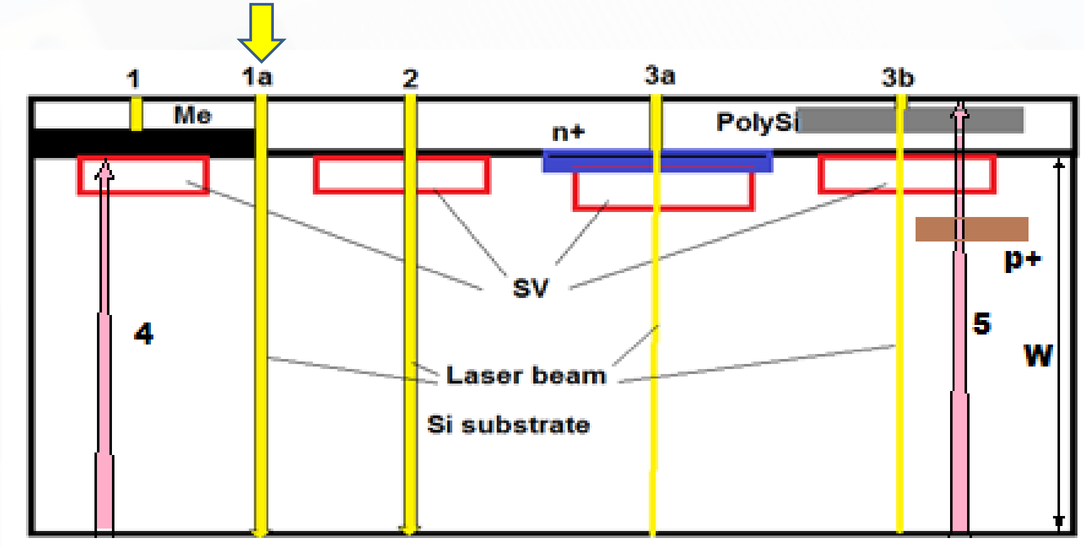
5 – Absorption in substrate and p$^+$

Relation between equivalent LET and laser pulse energy J_l :

Front-side: $$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot \frac{(1 - R_\lambda) \cdot J_l}{K_{opt\_los} \cdot \rho}$$

Backside: $$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot e^{-\alpha W} \cdot \frac{(1 - R_{\lambda 1}) \cdot (1 + R_{\lambda 2}) \cdot J_l}{K_{opt\_los} \cdot \rho}$$

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization

1a – Laser beam passes near metal stripe, but out of SV

Relation between equivalent LET and laser pulse energy J_l :

Front-side:

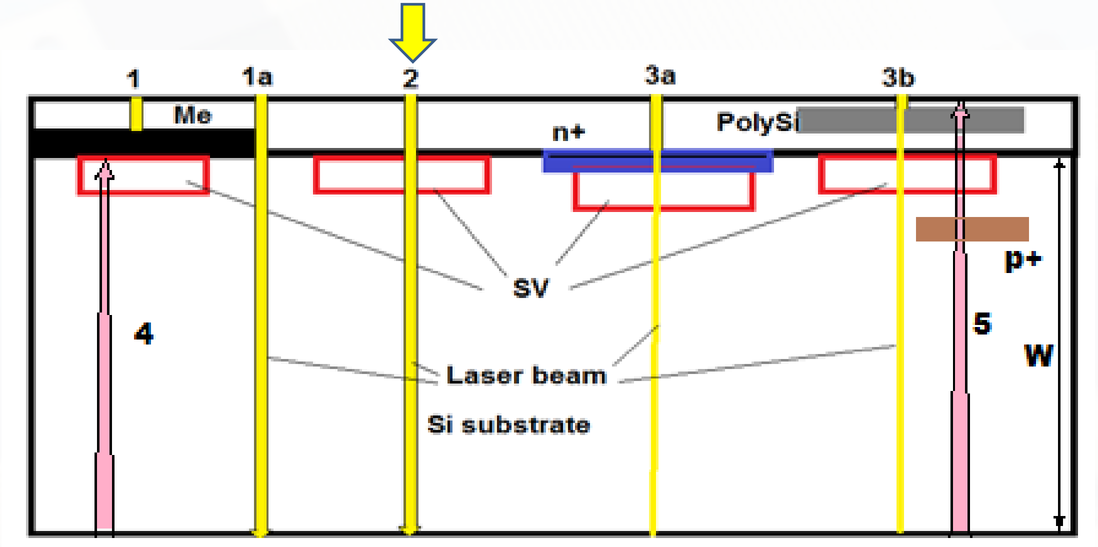
$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot \frac{(1-R_\lambda)\cdot J_l}{K_{opt\_los}\cdot \rho}$$

Backside:

$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot e^{-\alpha W} \cdot \frac{(1-R_{\lambda 1})\cdot(1-R_{\lambda 2})\cdot J_l}{K_{opt\_los}\cdot \rho}$$

SPELS

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization

1a – Laser beam passes near metal stripe, but out of SV

2 – Laser beam hits SV

Relation between equivalent LET and laser pulse energy J_l:

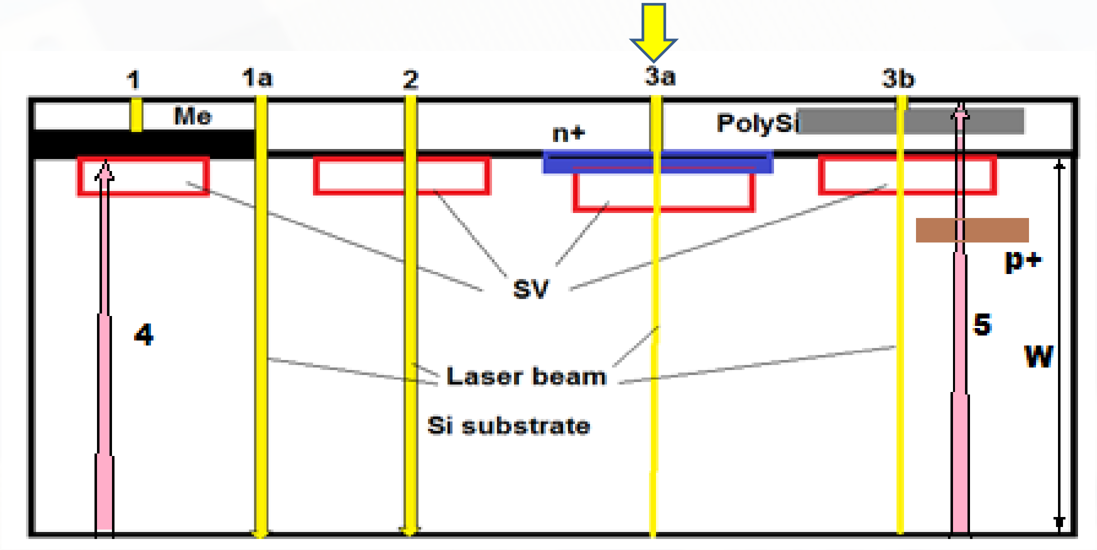
Front-side:

$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot \frac{(1-R_\lambda) \cdot J_l}{K_{opt\_los} \cdot \rho}$$

Backside:

$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot e^{-\alpha W} \cdot \frac{(1-R_{\lambda 1}) \cdot (1+R_{\lambda 2}) \cdot J_l}{K_{opt\_los} \cdot \rho}$$

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization

1a – Laser beam passes near metal stripe, but out of SV

2 – Laser beam hits SV

3a – Absorption in n$^+$-layer

Relation between equivalent LET and laser pulse energy J_l :

Front-side:

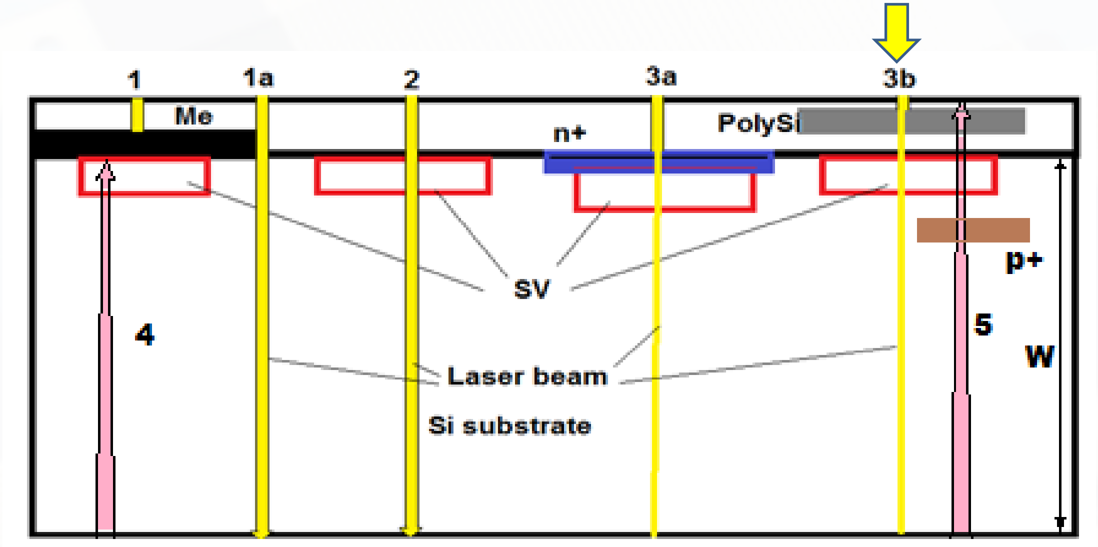
$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot \frac{(1-R_\lambda)\cdot J_l}{K_{opt\_los}\cdot \rho}$$

Backside:

$$LET \sim 1.8 \cdot 10^4 \cdot \alpha_0 \cdot \lambda \cdot e^{-\alpha W} \cdot \frac{(1-R_{\lambda 1})\cdot(1+R_{\lambda 2})\cdot J_l}{K_{opt\_los}\cdot \rho}$$

SPELS

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization
1a – Laser beam passes near metal stripe, but out of SV
2 – Laser beam hits SV
3a – Absorption in n^+-layer
3b – Absorption in poly-Si layer

Relation between equivalent LET and laser pulse energy J_l:

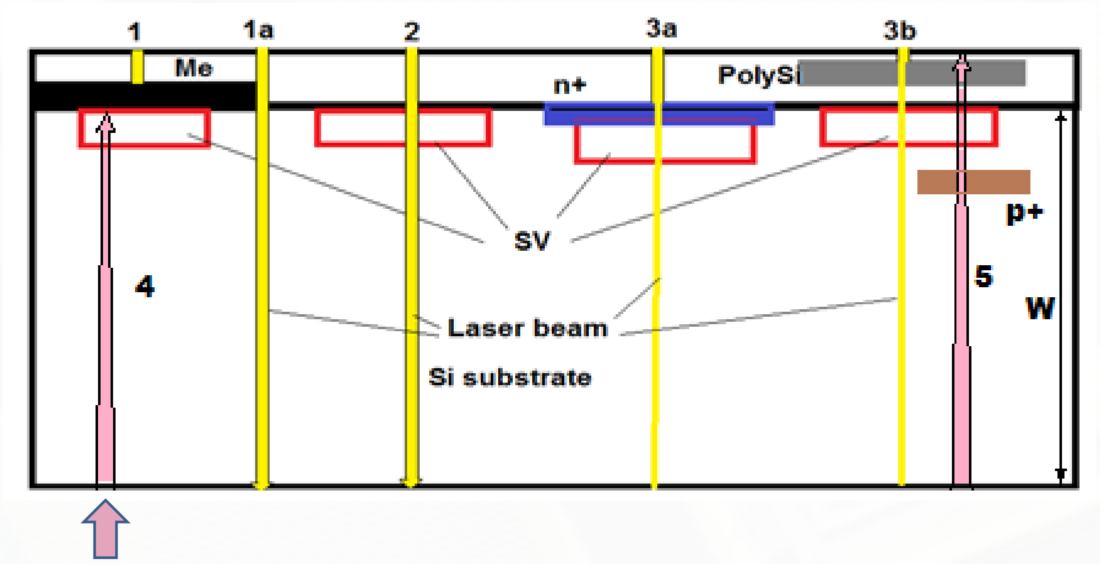
Front-side:

$$LET \sim 1.8\cdot 10^4\cdot \alpha_0\cdot \lambda\cdot \frac{(1-R_\lambda)\cdot J_l}{K_{opt\_los}\cdot \rho}$$

Backside:

$$LET \sim 1.8\cdot 10^4\cdot \alpha_0\cdot \lambda\cdot e^{-\alpha W}\cdot \frac{(1-R_{\lambda 1})\cdot (1-R_{\lambda 2})\cdot J_l}{K_{opt\_los}\cdot \rho}$$

• Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization
1a – Laser beam passes near metal stripe, but out of SV
2 – Laser beam hits SV
3a – Absorption in n^+-layer
3b – Absorption in poly-Si layer

Backside

4 – Absorption in substrate and reflection from metallization

Relation between equivalent LET and laser pulse energy J_l:

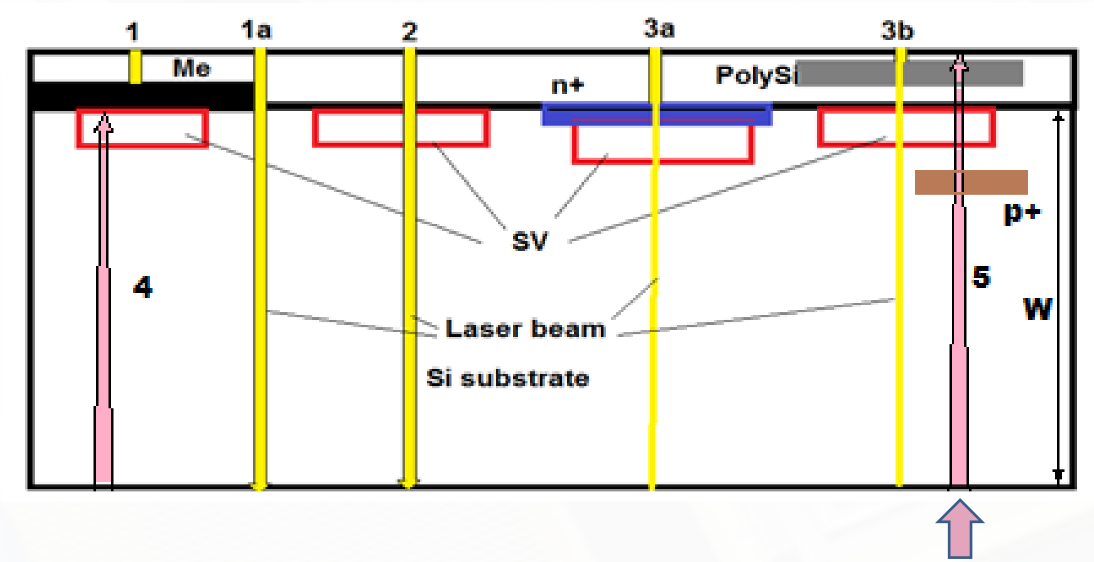
Front-side:

$$LET\sim1.8\cdot10^4\cdot\alpha_0\cdot\lambda\cdot\frac{(1-R_\lambda)\cdot J_l}{K_{opt\_los}\cdot\rho}$$

Backside:

$$LET\sim1.8\cdot10^4\cdot\alpha_0\cdot\lambda\cdot e^{-\alpha W}\cdot\frac{(1-R_{\lambda1})\cdot(1+R_{\lambda2})\cdot J_l}{K_{opt\_los}\cdot\rho}$$

Focused Laser Irradiation (FLI) technique



Front-side

1 – Sensitive volume (SV) is screened by metallization
1a – Laser beam passes near metal stripe, but out of SV
2 – Laser beam hits SV
3a – Absorption in n^+-layer
3b – Absorption in poly-Si layer

Backside

4 – Absorption in substrate and reflection from metallization
5 – Absorption in substrate and p^+

Relation between equivalent LET and laser pulse energy J_l :

Front-side:

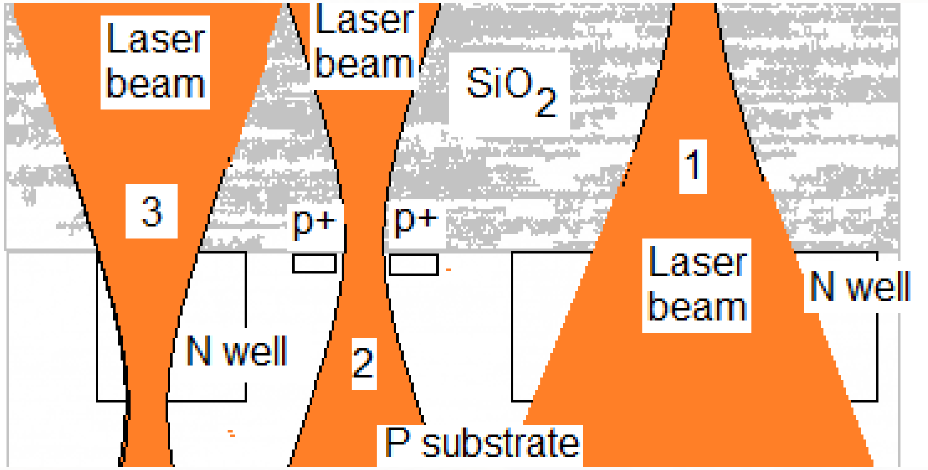
$$LET\sim 1.8\cdot 10^4\cdot \alpha_0\cdot \lambda\cdot \frac{(1-R_\lambda)\cdot J_l}{K_{opt\_los}\cdot \rho}$$

Backside:

$$LET\sim 1.8\cdot 10^4\cdot \alpha_0\cdot \lambda\cdot e^{-\alpha W}\cdot \frac{(1-R_{\lambda 1})\cdot (1+R_{\lambda 2})\cdot J_l}{K_{opt\_los}\cdot \rho}$$

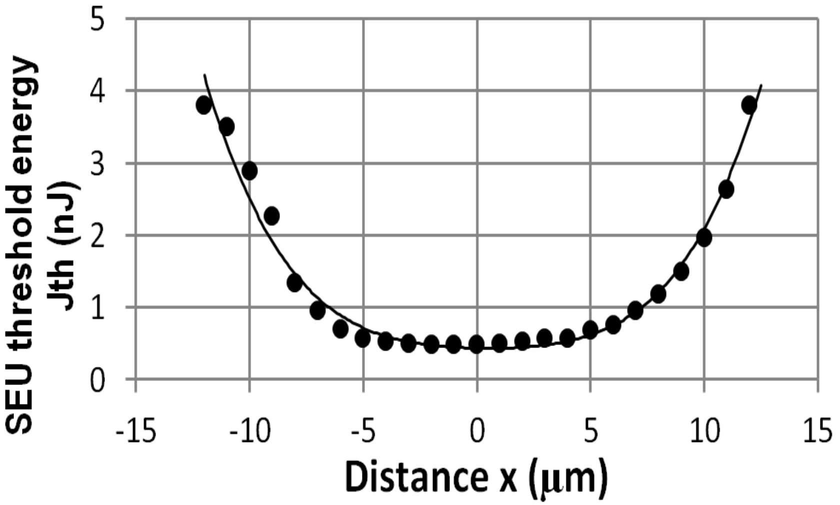
FLI technique accuracy depends on:

1) Beam waist at different depths from IC surface



1 – at the surface, 2 – at SiO$_2$-Si boundary,
3 – at well-substrate *p-n* junction

2) Beam Numerical aperture (NA)



Main reasons of relatively low accuracy

Non-uniformity of optical losses in IC →
inhomogeneity in the generation of charge carriers →
different values of K_{opt_los} at different points

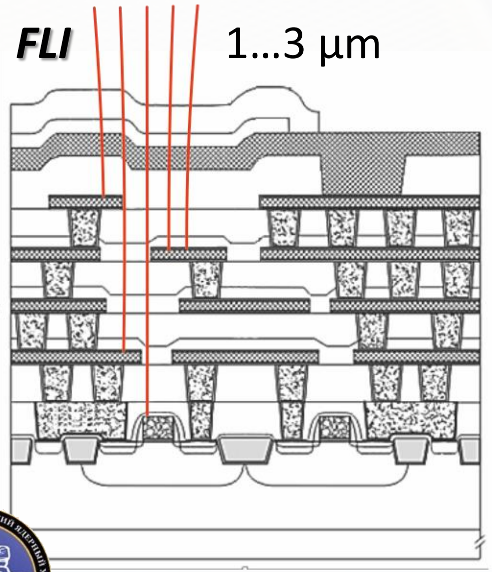
We fail to obtain reliable equivalent LET estimation by FLI technique when:

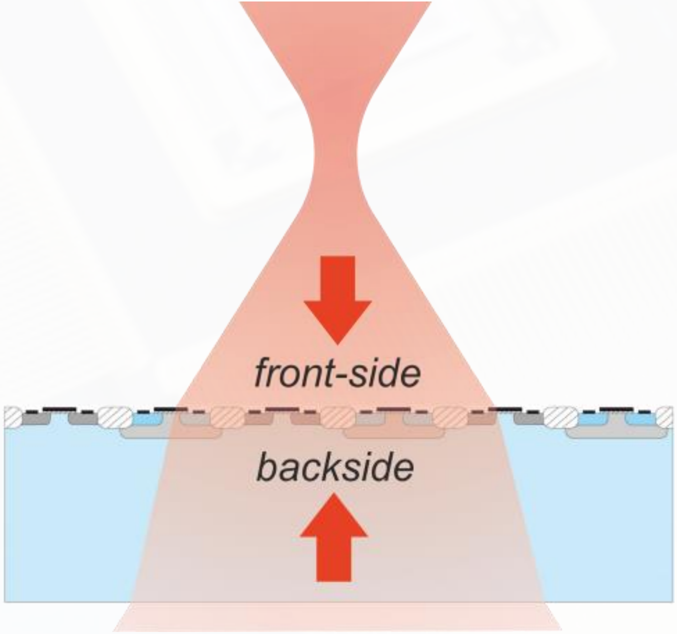
- Strong metallization or Flip-Chip IC; only low LET ions available for calibration, but substrate is too thick
- Functional areas have very large difference in elements density
- The most sensitive volume is under metallization layers – missed sensitive area (for front-side FLI)
- …

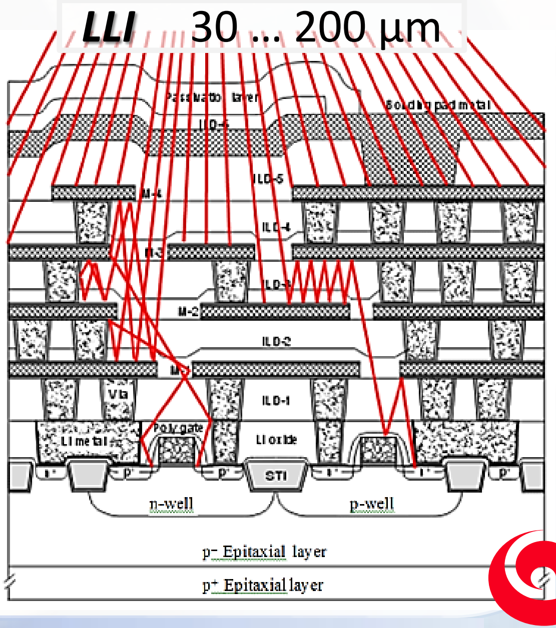
What is Local Laser Irradiation (LLI)?

For "local" *front-side* (***backside***) laser irradiation, the sample active layer must be positioned at some distance from the focal plane in the *divergent* (***convergent***) beam. "Local irradiation" with variable spot size from focused up to several hundreds of microns and with variable pulse energy must be capable to produce SEE in integrated circuit, but not causing so called "rail span collapse".

In *front-side* case, in addition to possible direct transmission through "metallization holes", the laser radiation may partially penetrate into the sensitive volume due to the divergence of the laser beam and such effects as single and multiple reflections, scattering, diffraction, secondary reflections from the air-SiO_2 boundary, interference, partial absorption in the n^+/p^+ layers of poly-silicon and reflection from the bottom of the substrate.







What is Local Laser Irradiation (LLI)?

Short answer: *It is variable "large spot" laser irradiation …*

LLI, as well as FLI, *is applicable for ICs with large sensitive areas*. For SEL effect, these large areas are the well-substrate p-n junctions.

But "large spot" laser irradiation
provides a natural averaging of the optical losses
making the account of their influence quantitatively more accurate.

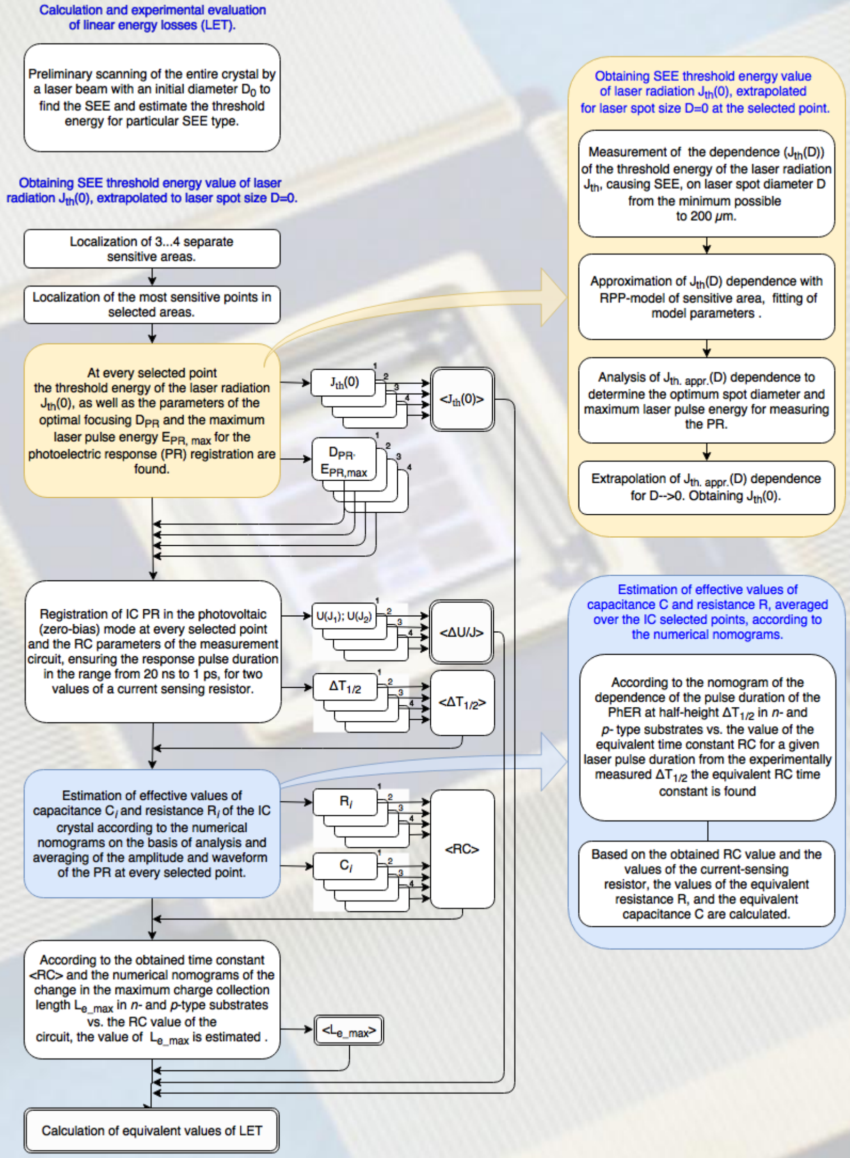
For SEU the sensitive areas are drains of MOS-transistors, which are much smaller than even focused laser beam's spot. However, even for SEU tests, we prefer LLI.

LLI *reduces the probability of missing an event* due better coverage of the crystal area with a larger spot during scanning.

	Spot size at active layer
FLI	1 … 3 µm
LLI	30 … 200 µm

• LLI technique algorithm, how it works?

Seems too sophisticated?



Calculation and experimental evaluation of linear energy losses (LET).

Preliminary scanning of the entire crystal by a laser beam with an initial diameter D_0 to find the SEE and estimate the threshold energy for particular SEE type.

Obtaining SEE threshold energy value of laser radiation $J_{th}(0)$, extrapolated to laser spot size D=0.

Localization of 3...4 separate sensitive areas.

Localization of the most sensitive points in selected areas.

At every selected point the threshold energy of the laser radiation $J_{th}(0)$, as well as the parameters of the optimal focusing D_{PR} and the maximum laser pulse energy $E_{PR,\ max}$ for the photoelectric response (PR) registration are found.

Registration of IC PR in the photovoltaic (zero-bias) mode at every selected point and the RC parameters of the measurement circuit, ensuring the response pulse duration in the range from 20 ns to 1 ps, for two values of a current sensing resistor.

Estimation of effective values of capacitance C_i and resistance R_i of the IC crystal according to the numerical nomograms on the basis of analysis and averaging of the amplitude and waveform of the PR at every selected point.

According to the obtained time constant <RC> and the numerical nomograms of the change in the maximum charge collection length L_{e_max} in *n*- and *p*-type substrates vs. the RC value of the circuit, the value of L_{e_max} is estimated .

Calculation of equivalent values of LET

Obtaining SEE threshold energy value of laser radiation $J_{th}(0)$, extrapolated for laser spot size D=0 at the selected point.

Measurement of the dependence ($J_{th}(D)$) of the threshold energy of the laser radiation J_{th}, causing SEE, on laser spot diameter D from the minimum possible to 200 μm.

Approximation of $J_{th}(D)$ dependence with RPP-model of sensitive area, fitting of model parameters .

Analysis of $J_{th.\ appr.}(D)$ dependence to determine the optimum spot diameter and maximum laser pulse energy for measuring the PR.

Extrapolation of $J_{th.\ appr.}(D)$ dependence for D-->0. Obtaining $J_{th}(0)$.

Estimation of effective values of capacitance C and resistance R, averaged over the IC selected points, according to the numerical nomograms.

According to the nomogram of the dependence of the pulse duration of the PhER at half-height $\Delta T_{1/2}$ in *n*- and *p*- type substrates vs. the value of the equivalent time constant RC for a given laser pulse duration from the experimentally measured $\Delta T_{1/2}$ the equivalent RC time constant is found

Based on the obtained RC value and the values of the current-sensing resistor, the values of the equivalent resistance R, and the equivalent capacitance C are calculated.

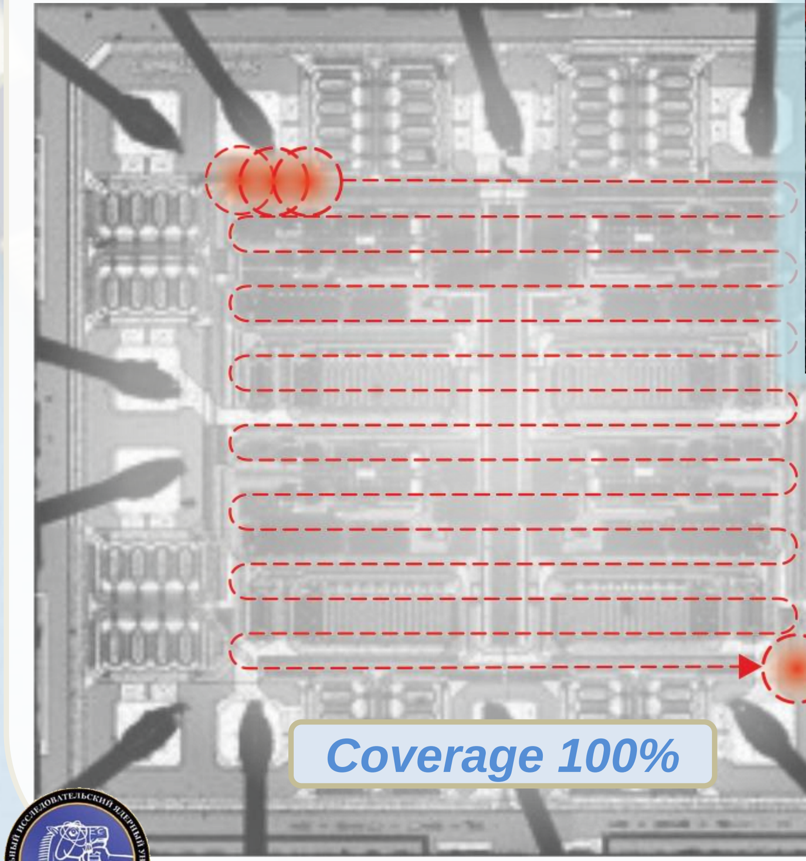
But it's worth it!

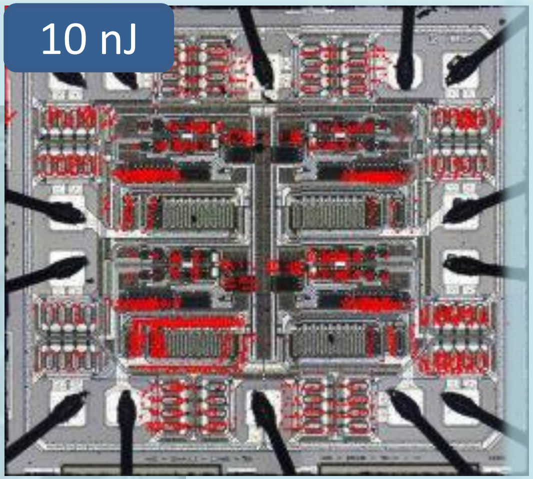
Stage 1

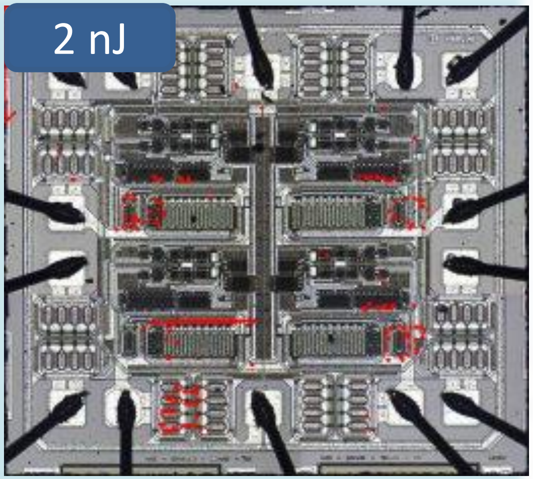
LLI technique algorithm

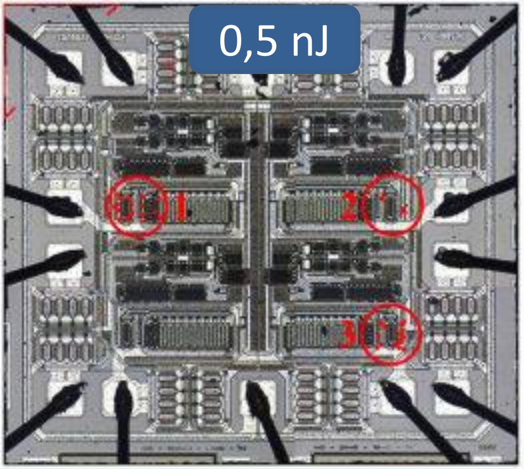
Automatic consequent scanning of the IC crystal using “large spot” (from 30 µm to 200 µm) irradiation for *n* (*n=3…4*) SEE sensitive areas localization.

(Scanning step) ≤ (Spot size/2)









Stage 1 results:

Center and dimensions of sensitive area

$(x_i, y_i); \Delta x_i; \Delta y_i$

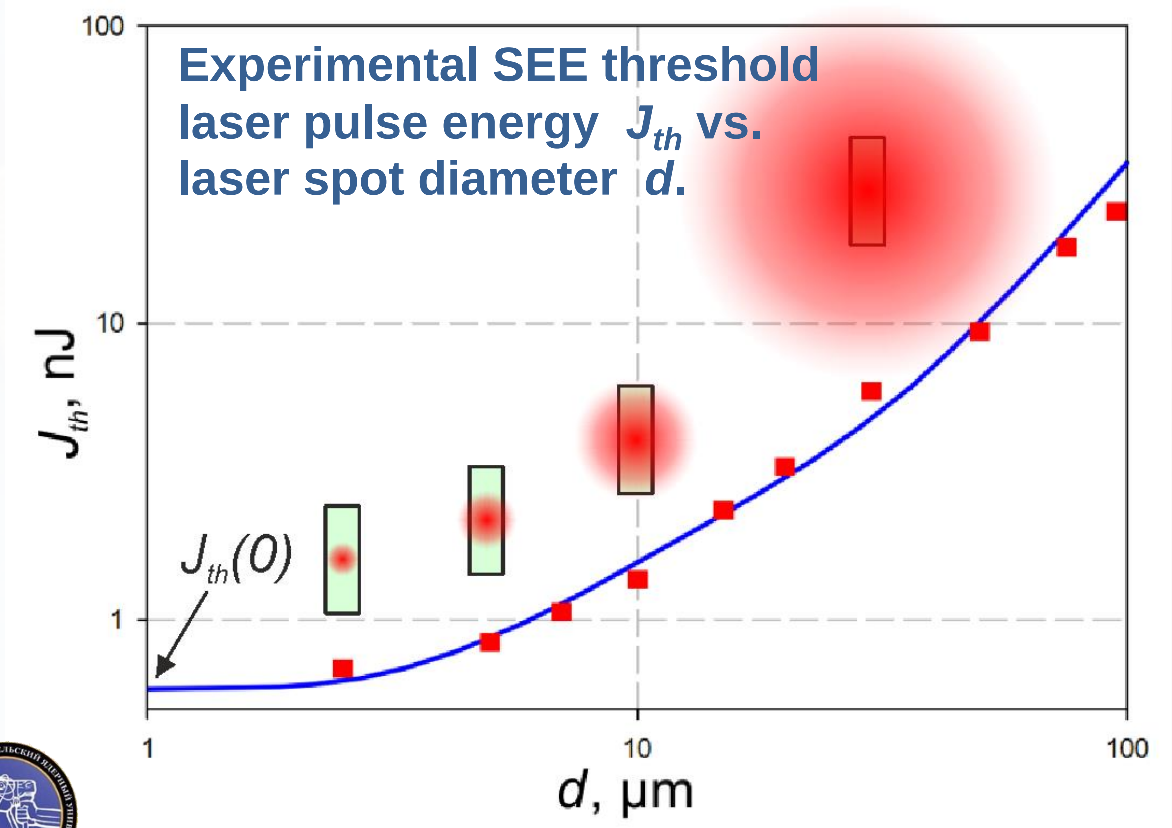
$i=1, 2,\ldots n$

Upper threshold pulse energy estimate

Stage 2

LLI technique algorithm

- Automatic scanning of each selected sensitive area with smaller spot size (down to 30 µm) and corresponding step to find the most sensitive point.
- Determination of SEE threshold energy values $J_{th}(0)$ of the laser radiation extrapolated to sharply focused in each selected sensitive point.



Experimental SEE threshold laser pulse energy J_{th} vs. laser spot diameter d.

Stage 2 results:

1) laser radiation threshold energy extrapolated to d -->0

$(J_{th}(0))_i$, $i=1, 2,\ldots n$

and averaged over n areas

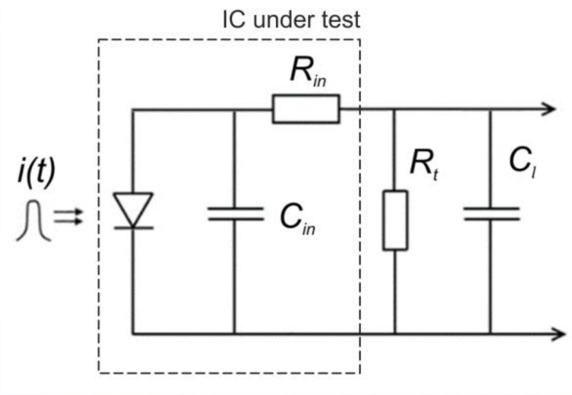
$<J_{th}(0)>$

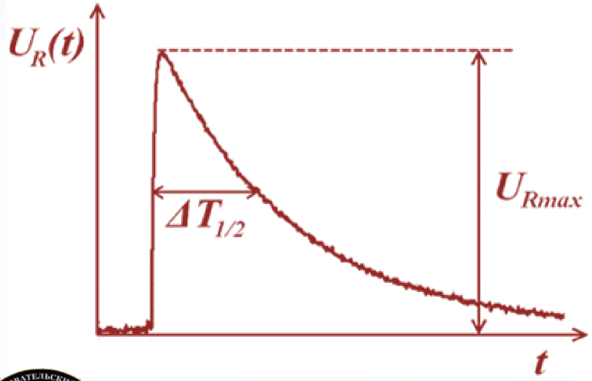
2) parameters of the optimal focusing d_{PR} and the maximum laser pulse energy $E_{PR,\ max}$ for the photoelectric response (PR) registration on Stage 3 .

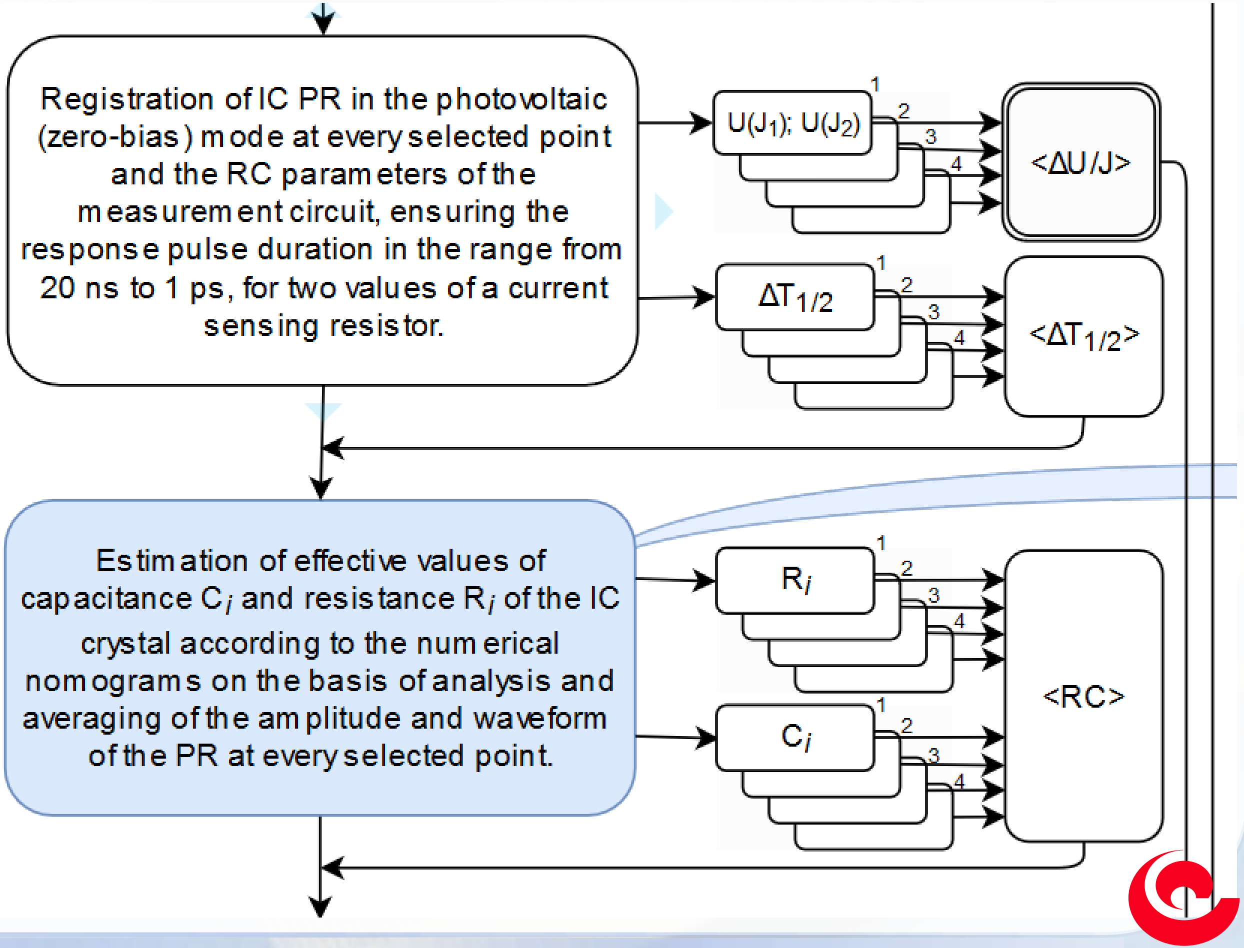
Stage 3

LLI technique algorithm

Estimation of the optical losses coefficient by measurement of the photoelectric response (PR) in power supply circuit under local laser irradiation in previously selected sensitive points.







Registration of IC PR in the photovoltaic (zero-bias) mode at every selected point and the RC parameters of the measurement circuit, ensuring the response pulse duration in the range from 20 ns to 1 ps, for two values of a current sensing resistor.

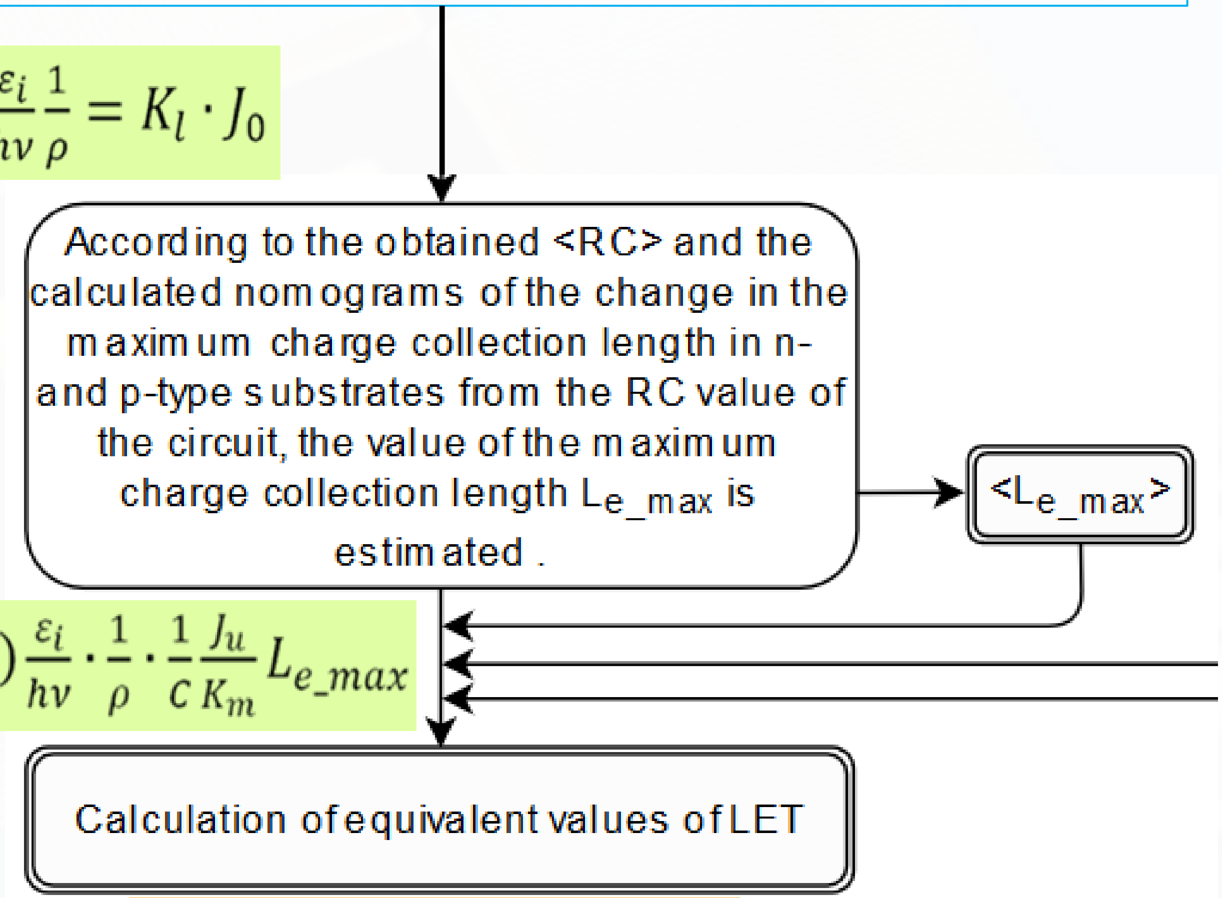
Estimation of effective values of capacitance C_i and resistance R_i of the IC crystal according to the numerical nomograms on the basis of analysis and averaging of the amplitude and waveform of the PR at every selected point.

Stage 4

LLI technique algorithm

Evaluation of the effective charge collection length using Stage 3 results

$$L_{z0} = \alpha_0(1 - R_\lambda)\frac{J_0}{K_m}\frac{\varepsilon_i}{h\nu}\frac{1}{\rho} = K_l \cdot J_0$$



According to the obtained <RC> and the calculated nomograms of the change in the maximum charge collection length in n- and p-type substrates from the RC value of the circuit, the value of the maximum charge collection length L_{e_max} is estimated .

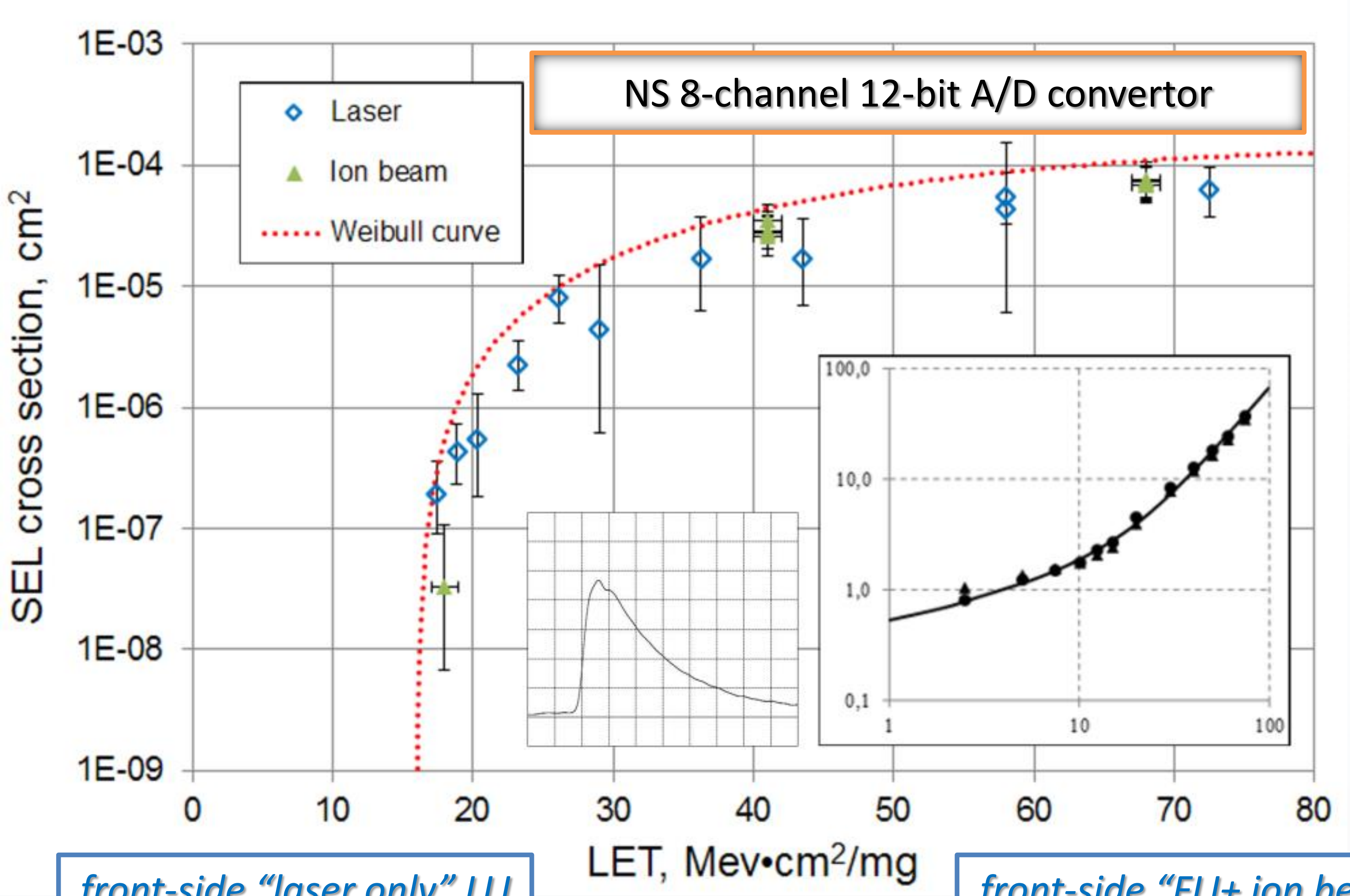
$<L_{e\_max}>$

$$U_{R\_max} = q \cdot \alpha_0 \cdot g_0(1 - R_\lambda)\frac{\varepsilon_i}{h\nu} \cdot \frac{1}{\rho} \cdot \frac{1}{C}\frac{J_u}{K_m} L_{e\_max}$$

Calculation of equivalent values of LET

$$L_{z0} = \frac{1}{q \cdot g_0}\frac{J_0}{J_u}\frac{C \cdot U_{R\_max}}{L_{e\_max}}$$

Qualification tests, based on LLI technique



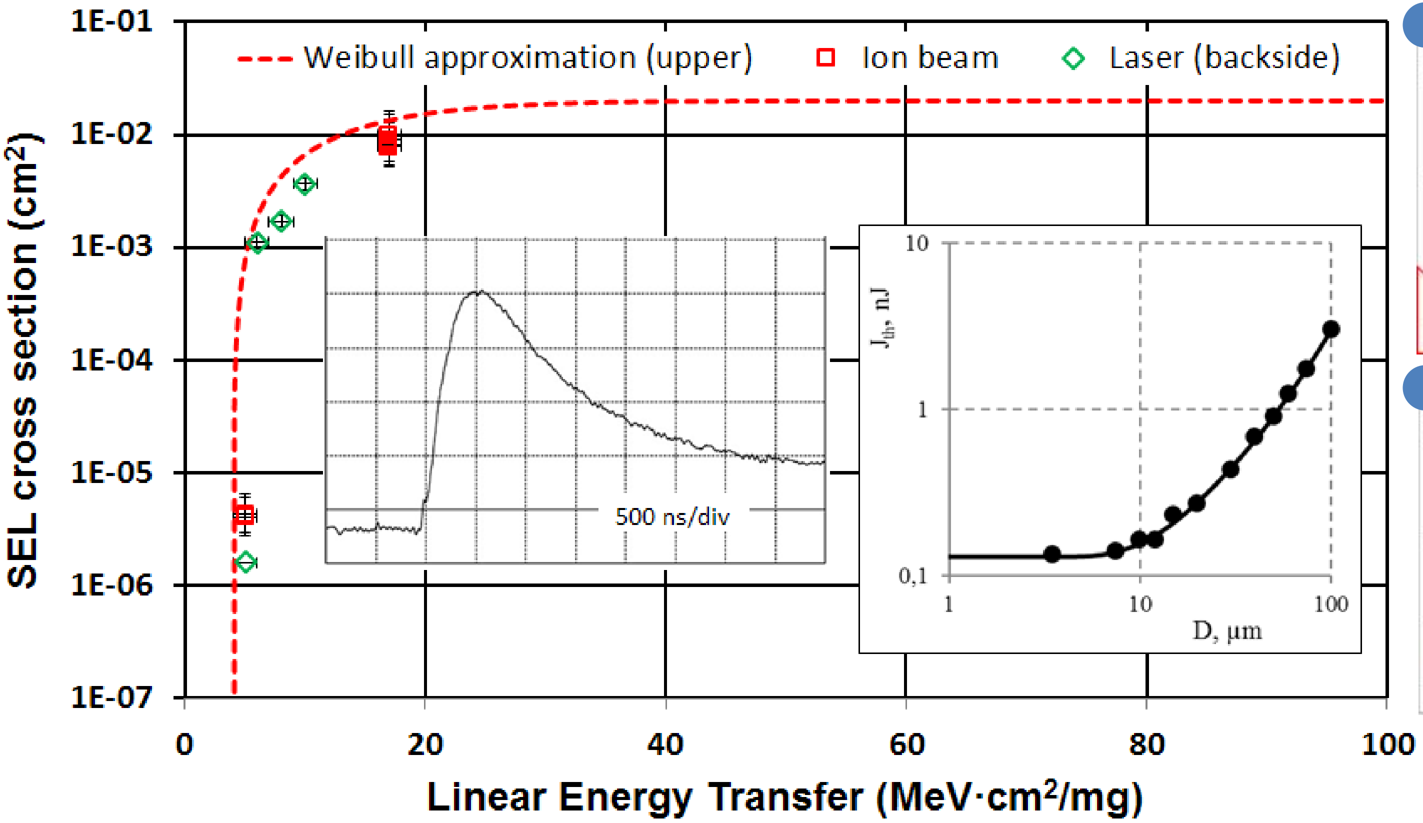
front-side "laser only" LLI
L_z = (10±5) MeV·cm²/mg

front-side "FLI+ ion beam"
L_z ≈ 15 MeV·cm²/mg

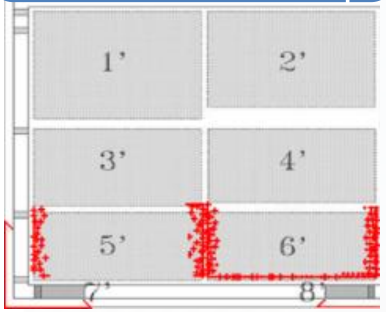
• Qualification tests, based on LLI technique

90nm SRAM test structure

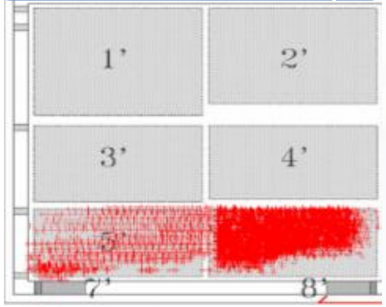
8 different topology blocks of 6-T memory cells



Front-side SEL map



Backside SEL map



backside "laser only" LLI
L_z = (4±2) MeV·cm²/mg

front-side "FLI+ ion beam"
L_z ≈ 5 MeV·cm²/mg

SEU threshold LET values for flip-chip VLCIs

VLCI type	*Technology*	$L_{th(SEU)}$, MeV·cm²/mg	
		LLI technique	Proton accelerator (published data)
Altera Stratix 2	90-nm, 1.2V, Cu	3	<14 (<2.8[1])
GX series	TSMC, low-k dielectric	20	<14*
Xilinx Virtex 4	90-nm, 1.2V, Cu	>100	>14
Xilinx Virtex 5	65-nm, 1.0V, Cu	45	>14
Xilinx Virtex 6	40-nm, 1.0V, Cu	20	>14 (>14[2])
Altera Stratix 3	65-nm, 1.1V, Cu	>100	>14
SoC	90-nm, 1.1V	6	<14

1. Single Event Upset Characterization of the Virtex-6 Field Programmable Gate Array Using Proton Irradiation. D.M.Hiemstra. IEEE Radiation Effects Data Workshop 2012 pp. 124-127
2. Single Event Effects Test Results for Advanced Field Programmable Gate Arrays. G. R. Allen, G.M. Swift. Radiation Effects Data Workshop, 2006 IEEE, July 2006 , 115-120

• LLI technique problems, new trends

Main problems:

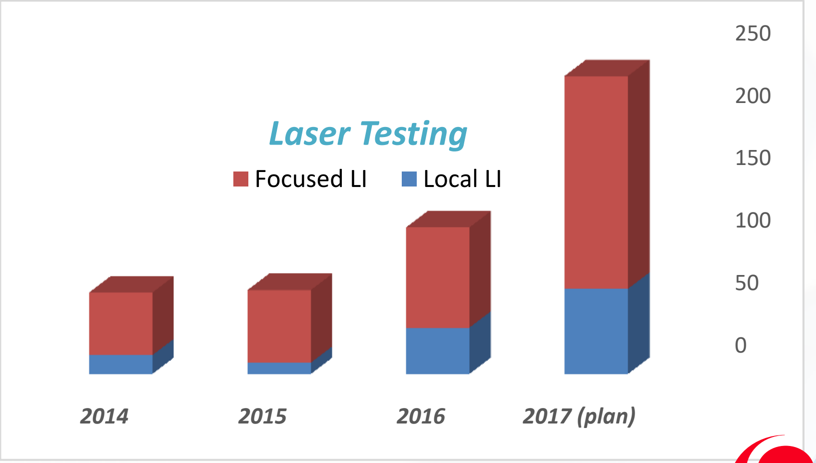
- uncertainty of some parameters (R, C, substrate);
- significant optical losses for front-side irradiation;
- too large difference in optical losses for different parts of modern VLCI.

Possible solutions:

- joint use of laser and pulsed X-ray facilities;
- mapping of electrical response over the whole IC crystal for further results correction;
- using backside irradiation with tunable wavelength (0.95–1.08 µm), allowing to avoid the excessive energy losses in thick substrates.
- Minimization of the uncertainty of laser beam focus position and laser spot size at active layer by using advanced IR camera, incorporated into focusing unit, and providing a simple and reliable way for automated sample positioning and tilt correction during backside scanning.

Conclusion

- There are two main SPA based laser irradiation techniques for SEE testing: focused and local.
- Focused laser irradiation technique is more simple (it requires only series of IC chip scans with varying pulse energy in order to determine the SEE’s cross section dependence), but it should be treated only as supplementary, though very effective add-on to the accelerator tests.
- Local laser irradiation technique seems to be more complicated (it includes experiment and numerical modeling for optical losses estimation), but it can be used as a stand-alone technique, not requiring the expensive accelerator tests.



Further reading

- O. B. Mavritskii, A. I. Chumakov, A. N. Egorov, A. A. Pechenkin, A. Yu. Nikiforov "Laser equipment for hardness evaluation of semiconductor elements exposed to heavy charged particles," Instruments and Experimental Techniques, 2016, Vol. 59, No. 5, pp. 627–649.
- A. I. Chumakov, A. N. Egorov, O. B. Mavritsky, A. V. Yanenko, "Evaluation of moderately focused laser irradiation as a method for simulating single-event effects," Russian Microelectronics, 2004, vol. 33, no. 2, pp. 106-110.
- A. I. Chumakov, A. A. Pechenkin, D. V. Savchenkov, A. S. Tararaksin, A. L. Vasil'ev, A. V. Yanenko, "Local laser irradiation technique for see testing of ICs," Proceedings of 12th European Conference on Radiation and Its Effects on Components and Systems (RADECS-2011), pp. 449- 453.
- A. A. Novikov, A. A. Pechenkin, A. I. Chumakov, A. O. Akhmetov, O. B. Mavritskii, "SEE laser testing at different temperatures," Proc. of the European Conf. on Radiation and its Effects on Components and Systems (RADECS-2015), 2015, art. no. 7365661, pp. 151-153.
- A. A. Pechenkin, D. V. Savchenkov, O. B. Mavritskii, A. I. Chumakov, D. V. Bobrovskii, "Evaluation of sensitivity parameters for single event latchup effect in CMOS LSI ICs by pulsed laser backside irradiation tests," Russian Microelectronics, 2015, vol. 44(1), pp. 33-39.
- A. I. Chumakov, A. A. Pechenkin, D. V. Savchenkov, A. V. Yanenko, L. N. Kessarinskiy, P. V. Nekrasov, A. V. Sogoyan, A. I. Tararaksin, A. L. Vasil'Ev, V. S. Anashin, P. A. Chubunov, "Compendium of SEE comparative results under ion and laser irradiation," Proc. of the European Conf. on Radiation and its Effects on Components and Systems, RADECS-2013, 2013, art. no. 6937390.
- D. V. Savchenkov, A. I. Chumakov, A. G. Petrov, A. A. Pechenkin, A. N. Egorov, O. B. Mavritskiy, A. V. Yanenko, "Study of SEL and SEU in SRAM using different laser techniques," Proc. of the European Conference on Radiation and its Effects on Components and Systems, RADECS-2013, 2013, art. no. 6937411.
- O. B. Mavritskii, A. N. Egorov, A. A. Nastulyavichus, A. A. Pechenkin, N. A. Smirnov, A. I. Chumakov, "NIR microscopy possibilities for the visualization of silicon microelectronic structure topology through the substrate", Physics Procedia, 2015, vol. 73, pp. 183-188.
- M. S. Gorbunov, B. V. Vasilegin, A. A. Antonov, P. N. Osipenko, G. I. Zebrev, V. S. Anashin, V. V. Emeliyanov, A. I. Ozerov, R. G. Useinov, A. I. Chumakov, A. A. Pechenkin, A.V. Yanenko, "Analysis of SOI CMOS Microprocessor's SEE Sensitivity: Correlation of the Results Obtained by Different Test Methods," IEEE Trans. on Nucl. Sci., 2012, vol. NS-59, no. 4. pp. 1130-1135.
- A. I. Chumakov, A. L. Vasil'ev, A. A. Pechenkin, D. V. Savchenkov, A. S. Tararaksin, A. V. Yanenko, "Single-event-effect sensitivity characterization of LSI circuits with a laser-based and a pulsed gamma-ray testing facilities used in combination," Russian Microelectronics, 2012, vol. 41, no. 4, pp. 221-225.
- A. I. Chumakov, "Interrelation of equivalent values for linear energy transfer of heavy charged particles and the energy of focused laser radiation," Russian Microelectronics, 2011, 40 (3), pp. 149-155

Thank you for your attention!